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A comprehensive review of solar facades. Transparent and translucent solar facades

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ABSTRACT

In the first paper of a series of two publications entitled "A comprehensive review of solar facades. Opaque solar facades" an exhaustive review of scientific studies carried out during the last decade on opaque solar facades was proposed. The paper dealt with facades that absorb and reflect the incident solar radiation but cannot transfer directly solar heat gain into the building. This article offers a complementary survey of studies conducted during the same period of time on transparent and translucent solar facades, highlighting the categories of ventilated facades and semi-transparent building-integrated photovoltaic facades.

Contents

1. Introduction

Nowadays, solar architecture or bioclimatic architecture has become one of the most promising alternatives to reduce energy consumption in buildings and so doing reduce the environmental damage that fossil fuels are causing all around the world. The solar facade is one important solution proposal. However, its implementation is accompanied by significant challenges in terms of complexity of processes and technologies involved and moreover with respect to the adaptability of these solutions to different geographical areas with particular climatic conditions. This has attracted strong interest from the international scientific community, which already has reported numerous studies related to solar facades.

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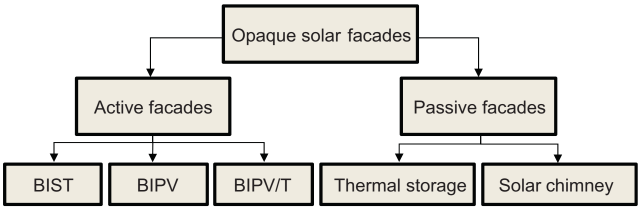


Fig. 1. Opaque solar facades classification (BIST: building-integrated solar thermal system, BIPV: building integrated photovoltaic system, BIPV/T: building-integrated photovoltaic thermal system).

In an earlier paper entitled "A comprehensive review of solar facades. Opaque solar facades" a review of the remarkable scientific studies carried out during the first decade of this century on facades that absorb and reflect the incident solar radiation but cannot directly transfer solar heat gain into the building was made. Fig. 1 shows a classification scheme of opaque solar facades regarding their principle of operation.

This paper aims to review scientific studies carried out during first decade of this century that pertain to transparent and translucent solar facades. Fig. 2 shows a quantitative summary of the literature reviewed.

2. Transparent and translucent active solar facades

The transparent and translucent solar facades not only absorb and reflect the incident solar radiation but also can transfer direct solar heat gain into the building. If such solar facades transform part of the incident sunlight into electricity directly or by transmitting the thermal energy into the building using electrical or mechanical equipment (pumps, fans, valves, control equipments), then they are called transparent and translucent active solar facades.

2.1. Mechanically ventilated transparent facade (MVF)

A mechanically ventilated facade (MVF) uses a mechanically assisted ventilation system to supply, expel or re-circulate air through a channel located between two transparent or translucent surfaces of the building envelope. The air removes heat from the cavity reducing the heating (winter) and cooling (summer) loads of the building, depending on the season and on the geographical zone (Fig. 3).

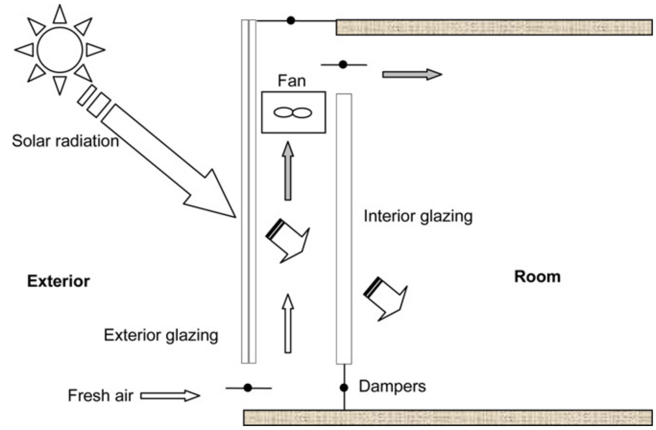


Fig. 3. Schematic diagram of a mechanically ventilated facade (MVF).

2.1.1. Theoretical and experimental study

Baker et al. [1] conducted a series of experiments to determine the performance characteristic of a supply air window used to pre-heat background room ventilation. A supply air window is a device that, by using the space between inner and outer sashes as an air path, enables ventilation air in winter to be pre-heated before it enters a room. A theoretical model of heat exchange conditions within the window was compared with results from a test cell. The test cell was used in different modes, firstly free-ventilated with the service room window and interconnecting duct to the cell left open, and then with forced ventilation at a consistent velocity to analyse the relative extent of direct solar and ventilation heat gain. The results indicate that there was a limited correlation between solar intensity and the extent of the temperature gradient within the window because the velocity of air movement through the window is substantially modified by the external wind speed. In another study, McEvoy et al. [2] carried out tests using a PASSYS test cell to determine the appropriate dimensional characteristics for the supply air window, and the correct location of a low emissivity (low-E) coating within the glazing assembly. The performance of the window was monitored relative to climate conditions measured at an adjacent weather station. They concluded that solar pre-heating performance diminished when the ventilation rate increased. At an air flow rate of 13 l/s, pre-heating supplied 50% of the ventilation heat load when the incident solar energy was 800 W/m^2, and 75% at 8 l/s. In a subsequent work, Southall and McEvoy [3] studied the followings characteristics of the supply air window: radiative solar gain factor (gr-value) as a function of solar radiation, external window U-value (Ue) variation with window size, ventilation gain factor (gv-value) as a function of solar radiation and window preheat as a function of window size. These characteristics have been established by laboratory, test cell investigations, and simulations using computational fluid dynamics and ESP-r, a whole building dynamic thermal modeling tool.

Zöllner et al. [4] described the experiments performed in an outdoor test stand for so-called "double-skin-facades" at the Technical University of Munich. The purpose of the investigation was to determine the time and local averaged overall heat transfer coefficients

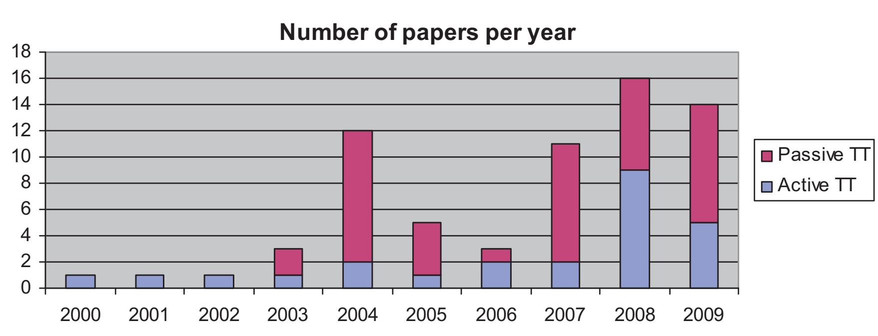


Fig. 2. Papers distribution per year (TT: transparent–translucent).

for solar radiation augmented turbulent mixed convection flows in transparent vertical channels. Detailed parameter analysis for a box-window of typical geometry (height of the box window, $H = 2.4$ m, distance between external and internal facades, $S = 0.6$ m, height of the horizontal ventilation gratings, $h = 0.1$ m) with a solar irradiation of about 600 W/m^2 and a decrease in outdoor temperature from 26 °C down to 5 °C yielded an increase in the average mean Nusselt number of about 20%. Whereas, an increase in the solar irradiation from 500 to 900 W/m^2 resulted in an increase in the average mean Nusselt number of about 25%.

Safer et al. [5] proposed a comprehensive modeling of a compact double-skin facade equipped with a venetian blind and forced ventilation. The modeling is done using the CFD (computational fluid dynamics) approach to assess the air movement within the ventilated facade channel. The commercial CFD tool FLUENT 6.0.20 was used in this study. Three-dimensional airflow is modeled using a homogeneous porous media representation, in order to reduce the size of the mathematical model. A parametric study is proposed [5], analyzing the impact of three parameters on the airflow development: slat tilt angle, blind position and air outlet position. The distance between the blind and the external glazing was found to have a major impact on the velocity profiles inside the double-skin facade channel.

Balocco and Colombari [6] proposed a non-dimensional analysis as a method to analyze mechanically ventilated double glazed facade energy performance. The 12 non-dimensional numbers defined can be used to describe thermal and energy performance of interactive facade designs. The results revealed a strong correlation between Nusselt numbers calculated with experimental data and those obtained by the validated multivariable correlation function.

Gosselin and Chen [7] proposed a four step computational method that uses both computational fluid dynamics and coded radiation calculations to determine airflow and heat transfer through an airflow window. Experimental tests on a full-scale dual-airflow window system were used to obtain various indoor and outdoor air and window surface temperatures for validating the computer method. The difference obtained between the computed air and surface temperatures and the measured data was less than 1 K.

Jiru and Haghighat [8] presented the application of the zonal approach for modeling airflow and temperature in a ventilated double skin facade (DSF). The zonal airflow equation, power-law, was employed to calculate the airflow through the shading device and cavities. The zonal energy equation was used to evaluate the temperature distribution in the DSF system. The inlet–outlet temperature difference increased as height of the DSF increased and when venetian blinds were installed but it was found to decrease as the airflow rate increased.

Guardo et al. [9] evaluated, by means of computational fluid dynamics (using software Fluent 6.3), the influence of several construction and operation parameters of the active transparent facades (ATFs), such as optical properties of the materials, geometrical relations of the facade or flow stream conditions, in terms of energy savings, measured as a reduction of the solar load entering the building. It was seen that an increase of the length-to-depth ratio causes a decrease on the ATF efficiency in terms of solar load gains. For the tested cases, an increase on the turbulence intensity does not lead to improvements in the reduction of solar load gains.

Haase et al. [10] evaluated different ventilated facade designs in respect to energy savings. Thermal building simulations (TRNSYS) were linked to nodal airflow network simulations (COMIS) for detailed ventilated double-skin facade performance. In order to validate the model, simulations were carried out on an office building in Lisbon. The study showed that it is difficult to simulate the individual users behavior for controlling the roller blinds. Three simulations with different assumptions illustrated that the black roller blind is largely responsible for high gap temperatures. A white coloured roller blind reduced gap temperatures by 11 K.

Fuliotto et al. [11] presented a decoupling method capable to evaluate thermal performances and analyze fluid phenomena in double-skin facade (DSF). The solar radiation effects were evaluated with an analytical model and computational fluid dynamics simulations were used to evaluate complex flow and thermal effect on a commercial DSF. With the decoupling approach to account for the effects of solar radiation and flow, the numerical results obtained by the CFD approach agreed well with the experimental data collected on a full scale test room with a ventilated DSF.

Gavan et al. [12] showed the results of an experimental campaign performed on a full-scale facility provided with a DSF. The tests involved a DSF with a common type of sun-shading device (venetian blinds) located between the two skins. Analysis of the temperature profiles inside the DSF and the test cell showed that the surface and air temperatures are mainly determined by the DSF sun-shading device angle and secondly by the DSF airflow rate. If the sun-shading device is closed, the outdoor air cavity of the DSF and the sun-shading device itself will have higher temperatures than if it is opened.

Serra et al. [13] presented the results of an extensive experimental campaign on a climate facade with a mechanically ventilated air gap, carried out at the Department of Energetics at the Politecnico di Torino. Measurements were performed utilizing the TWINS (Testing Window Innovative Systems) test facility. Comparing the performance of the active facade to the reference one, they affirmed that the climate facade showed a better performance in each season and for each configuration, considering both energy efficiency and thermal comfort performance issues.

2.1.2. Development

Corgnati et al. [14] presented an extensive measurement campaign performed on an active transparent facade during actual operating conditions. The main aims of the research were: to assess the actual facade performance, both in terms of energy savings and enhanced comfort conditions, to obtain more detailed knowledge of its thermofluid dynamic behavior and to highlight the weak points (overheating of the facade and low air pre-heating efficiency) of this relatively new technology that still requires further improvement. The analyzed component consisted of a transparent mechanically ventilated facade integrated with an HVAC (heating, ventilating, and air conditioning) system.

Fallahi et al. [15] introduced an innovative design approach involving the integration of passive thermal mass technique with the air channel of the conventional double-skin facade. A numerical model was developed, capable of determining the thermal performance of the conventional DSF. The simulation results revealed that mechanically ventilated DSF can save energy based on configuration from 21% to 26% in summer and from 41% to 59% in winter as compared to conventional DSF without thermal mass.

2.1.3. Feasibility study

Saelens et al. [16] described how to optimize the energy performance of single-story multiple-skin facades (MSF) by changing the settings of the facades and HVAC-system according to the net energy demand of the building. The annual energy performance was analyzed for typical Belgian climatic conditions using the software TRNSYS 15.3.

Haase and Amato [17] evaluated the possibility of designing an energy efficient double-skin facade (DSF) for warm and humid climate. For this study, TRNSYS and TRNFLOW were used to model an office room with DSF. A new type of airflow window to control the exhaust airflow that can help to reduce cooling load of an office up to almost 40% was proposed.

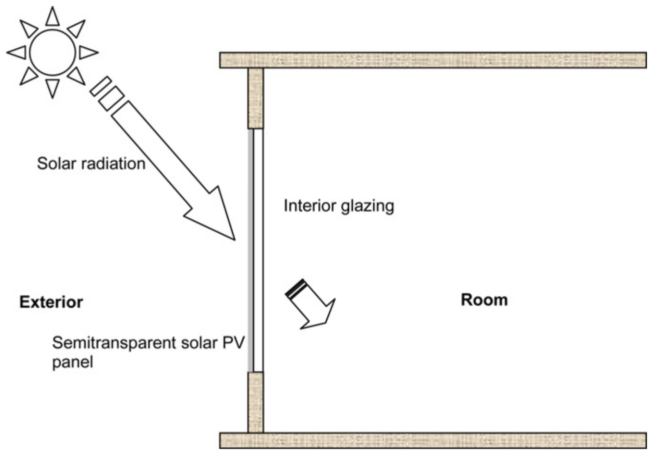


Fig. 4. Schematic diagram of semi-transparent building-integrated photovoltaic system (STBIPV).

2.2. Semi-transparent building-integrated photovoltaic system (STBIPV)

A semi-transparent building-integrated photovoltaic system (STBIPV) is integrated into the building envelope generating electricity via photovoltaic modules and allowing daylight entering into the interior spaces (Fig. 4).

2.2.1. Theoretical and experimental study

Fung and Yang [18] presented a one-dimensional transient heat transfer model, the Semi-transparent Photovoltaic module Heat Gain (SPVHG) model, for evaluating the heat gain of semi-transparent photovoltaic modules for building-integrated applications. The annual total heat gain was evaluated by using the SPVHG model. It was found that the area of solar cells in the PV module has significant effects on the total heat gain, since nearly 70% of total heat gain can be reduced if the solar cell area ratio is 0.8.

Song et al. [19] characterized the power output of PV module depending on incidence angle and the azimuth using a transparent thin-film solar cell in a mock-up model at various slopes to the south, as a building integrated photovoltaic system. It was found that the PV module with a slope of 30°, facing south, provided the best power performance in terms of annual power output (844.4 kWh/kWp annual power output). It produced about 2.5 times higher power output than the module with the vertical slope.

Han et al. [20] analyzed numerically the steady natural convective airflow in a novel type glazing system with integrated semi-transparent photovoltaic cells using a stream function vorticity formulation. Based on the resulting numerical predictions, the effects of Rayleigh numbers on airflow patterns and local heat transfer coefficients on vertical glazing surfaces were investigated for Rayleigh numbers in the range of $10^3 \leq Ra \leq 2 \times 10^5$. In the case of lower Rayleigh numbers, i.e. $Ra = 10^3$, the dominant mode of heat transfer was observed by conduction, while for $Ra > 10^3$ the airflow exhibited circulation patterns as the fluid motion was affected by both vertical heated and cooled glass panes. In addition, the effect of the air gap thickness in the cavity on the heat transfer through the cavity was evaluated and the optimum thickness of the air layer was found to be in the range of 60–80 mm.

Park et al. [21] investigated the electrical and thermal performance of a semi-transparent PV module that was designed as a glazing component. The experiment was performed under both Standard Test Condition (STC) and outdoor conditions. The results showed that the power decreased about 0.48% (in STC) and 0.52% (in outdoor conditions, under 500 W/m^2) per 1 °C increase of the PV module temperature. It was also found that the property of the glass used for the module affected the PV module temperature followed by its electrical performance, confirming that during a winter day, the PV module with the bronze glass had a higher temperature compared to the module with clear glass.

2.2.2. Development

Phani et al. [22] discussed the Titania solar cell structure and operating principles and its performance advantages and applications with special focus on the performance of Titania solar cells as vertically mounted building products. The Titania cell consists of a sandwich of a TiO_2, sensitizing dye, electrolyte and catalyst between two conductive transparent electrodes. Unlike conventional crystalline silicon solar cells, the Titania cell can be fabricated to be visually transparent. The authors presented the Titania solar cell's performance advantages over other solar cells, which include the ability to perform well in low light and shade, and to improve its performance with increasing temperature.

Xu et al. [23–25] studied two types of commercial available thermoelectric (TE) modules for their potential application in an active building envelope (ABE) prototype window system. ABE systems are a new enclosure technology which integrates photovoltaic and TE technologies In ABE systems. According to the experimental data and simulation results, the current ABE window prototype affected indoor temperature of the testing room with 2–6 °C. They established that the overall efficiency is about 5% when the prototype was operating in a cooling mode, and 13% when operating in a heating mode.

Mercaldo et al. [26] presented an analysis on architectural issues and technological developments of thin film silicon photovoltaic, in particular related to transparent and conductive oxide (TCO) and thin film amorphous and microcrystalline silicon solar cells. They pointed out the advantages of the thin film photovoltaic technology for building integration, for retrofit and in particular for innovative interventions, showing examples of contemporary architectures requiring the use of very versatile photovoltaic modules. They observed a high transparency (>82%) in the whole wavelength range of photovoltaic interest.

2.2.3. Feasibility study

Spanos and Duckers [27] examined the actual costs of electricity produced by photovoltaic generators placed on buildings in UK and Greece. The analysis has been done with the aid of PVSYST software. Concerning the PV glazing systems, which preserve high transparency, and can replace conventional glazing materials, they concluded that, even if the system is not at a favourable tilt angle, the reduction in cost of generated electricity from integrated systems is 32% and 16% for UK and Greece, respectively, in relation to a not integrated structure.

Alnaser et al. [28] studied the possibility to externally renovate the Almoayyed Tower and the Bahrain International Circuit (Formula 1 Circuit), in Bahrain, using PV as a facade and on the roof top. They determined that the PV panels installed on the 12,000 m^2 total windows of the Bahrain International Circuit, could provide 45.3×10^6 kWh per year of electrical energy.

Bahaj et al. [29] explored technical, economic, environmental and indoor comfort implications of emerging glazing technologies for energy control of highly glazed buildings in arid Middle Eastern climates. The work included predictions through simulation of the impact of third generation thin films (conversion efficiencies of 60% or greater) on the Jumeirah beach hotel in Dubai. The simulations predicted that such a PV solution covering 40% of the glazed area would produce a facade which can address the externally driven air-conditioning load in its entirety with a surplus electricity generation of 1542 kWhe/year.

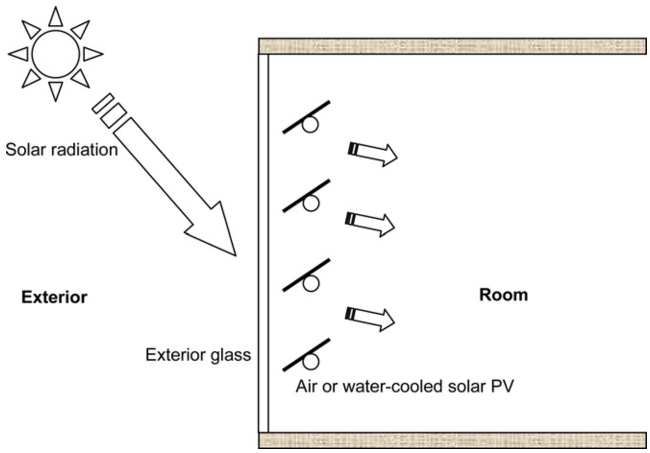


Fig. 5. Schematic diagram of semi-transparent building-integrated photovoltaic thermal (STBIPV/T).

Chow et al. [30] reported the findings on the energy performance of “see-through” photovoltaic glazing as applied to a typical open-plan office environment of Hong Kong. An experimental system was first set up and the measurements were used to verify the theoretical models developed via the ESP-r simulation platform (integrated energy modeling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems). The semitransparent single glazing PV system was found able to save 23% of the electricity consumed in space cooling per year, whereas the semitransparent natural-ventilated double-glazing PV system was able to save 28%.

Li et al. [31] studied the thermal and visual properties, energy performance and financial issue of a semi-transparent photovoltaic as a building component. Case studies based on a generic reference office building were conducted to elaborate the energy and cooling requirements, and the cost implications when the PV facades together with the daylight-linked lighting controls were being used. The findings showed annual building electricity saving of 1203 MWh, peak cooling load reduction of 450 kW, and annual emissions reduction of CO_2, SO_2, NO_x and particulates, respectively by 852, 2.62, 1.45 and 0.11 tons, when semi-transparent PV panels together with the dimming controls were used.

2.3. Semi-transparent building-integrated photovoltaic thermal system (STBIPV/T)

A semi-transparent building-integrated photovoltaic thermal (STBIPV/T) system combines the functions of a building-integrated photovoltaic (BIPV) system with those of a building-integrated solar thermal (BIST) system and also allowing daylight entering into the interior spaces (Fig. 5).

2.3.1. Development

Davidsson et al. [32] developed and evaluated a building-integrated multifunctional photovoltaic–thermal solar window. It is constructed of PV cells laminated on solar absorbers placed in a window behind the glazing. A model for simulation of the electric and hot water production was developed. The simulation program was calibrated against measurements on a prototype solar window placed in Lund in the south of Sweden and against a solar window built into a single family house, Solgården, in Älvkarleö in the central part of Sweden. The results from the simulation showed that the solar window annually produces about 35% more electric energy per unit cell area compared to a vertical flat PV module, because the wall mounted PV module benefits less from the diffuse radiation compared to the solar window due to less favourable view angles between the cells and the sky.

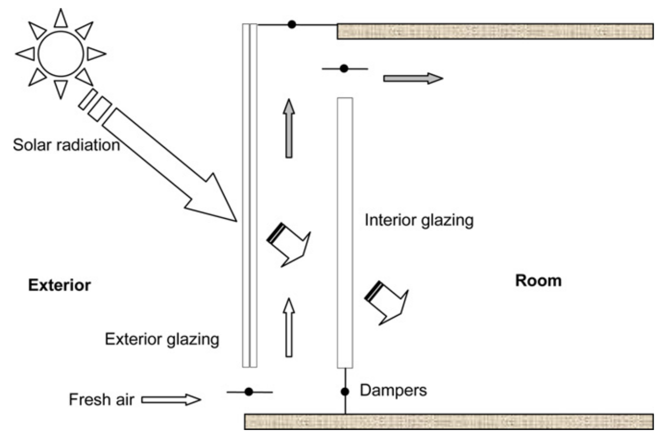


Fig. 6. Schematic diagram of naturally ventilated facade (NVF).

2.3.2. Feasibility study

Infield et al. [33] explored different approaches to thermal performance estimation for ventilated photovoltaic facades. In particular, an extension of the familiar heat loss and radiation gain factors (*U* and *g* values, respectively) has been employed to take account of the energy transfer to the facade ventilation air. This approach has been applied to the ventilated PV facade of the public library at Mataró, Spain. A mean thermal efficiency over the data of 25.8% was obtained.

3. Transparent and translucent passive solar facades

The transparent and translucent passive solar facades may be surface glazed so they transform the incident sunlight into thermal energy, for heating or ventilation purposes of the building, without using electrical or mechanical equipment (pumps, fans, valves, control equipments) and also allow the transfer of direct solar heat gain into the building.

3.1. Naturally ventilated transparent facade (NVTF)

A naturally ventilated facade (NVF) supply, expel or re-circulate air through a channel located between two transparent or translucent surfaces of the building envelope by means of wind pressure and/or the natural convection. The air removes heat from the cavity reducing the heating (winter) and cooling (summer) loads of the building, depending on the season and on the geographical zone (Fig. 6).

3.1.1. Theoretical and experimental study

Faggembauu et al. [34,35] presented a code for the numerical simulation of ventilated and conventional facades. It was based on time-accurate, one-dimensional discretization for the channel and the different solid zones, and allows heat fluxes and temperature distributions in the facade to be obtained over the course of one year. The numerical code allowed advanced elements to be integrated into the facade, such as phase change materials, selective surfaces and improved glasses.

Balocco [36] proposed a method based on dimensional analysis for a natural ventilated double facade energy performance study. The 12 non-dimensional numbers defined, with physical meaning, can be used to describe thermal and energy performance of different facade designs. Results showed Nusselt numbers calculated with experimental data, and those obtained by multivariable

function correlating the 12 non-dimensional groups, well fitted the regression line.

Park et al. [37] described the calibration of a simulation model of double-skin facade systems with controlled rotating louvers and ventilation openings. The approach is based on a parameter estimation technique and in situ monitoring of a full-scale element mounted on the south facing facade of an existing building. This new approach is based on a postulated “minimalistic” lumped model, which is calibrated on in situ measurements. It is found that the calibrated model is surprisingly accurate and ideally suited for use in the ensuing optimal control and performance studies. They also [38] developed a real-time optimization of a double-skin facade system for the so-called smart facade systems. It optimizes the performance of the system by rotating a motorized louver slat in the cavity and ventilation dampers at the top and bottom of exterior and interior glazing. Users interaction with the system is Web enabled. Current state variables, weather data and energy flows are posted on a web page and an occupant with given privileges can choose the preferred operation mode or override the devices (louvers, ventilation inlet/outlet).

Saelens et al. [39] studied the importance of a correct modeling of the inlet temperature of ventilated multiple-skin facades. Measurements demonstrate that the assumption of an inlet temperature equal to the interior or exterior air temperature is usually not valid. Their sensitivity study illustrates the significance of the inlet temperature as a boundary condition for numerical multiple-skin facade models. Finally, the inlet temperature model and multiple-skin facade model are used in a whole building energy simulation to indicate the importance of a correct inlet temperature on the energy performance.

Ismail and Henríquez [40] presented a mathematical model and the results of numerical simulations of a double sheet ventilated glass window. The two-dimensional transient model is formulated based upon the fundamental equations of mass, momentum and energy conservation, the associated constant and time varying boundary conditions and is solved by finite difference approach and the alternating direction implicit scheme.

Xamán et al. [41] investigated numerically the laminar and turbulent natural convection flow in a two-dimensional tall rectangular cavity heated from the vertical side for aspect ratios of 20, 40 and 80. The finite volume method was used to solve the conservation equations of mass, momentum and energy for Rayleigh numbers from 10^2 to 10^8, the flow was considered either laminar or turbulent.

Hien et al. [42] investigated the effects of a double glazed facade with ventilation systems on the energy consumption, thermal comfort and condensation and compared it to a single glazed facade system. A multi-zone simulation software for energy consumption, thermal comfort issue and condensation problems was utilized to predict the behaviors of single glazed facade building as well as double glazed facade building. This study recommended the operation of mechanical fans to maintain lower internal surface temperatures and to remove the condensation in the double-glazed cavity.

Manz and Frank [43] presented a method based on the coupling of three different types of simulation models that is economical in terms of computing time, and thereby, suitable for design purposes. These models are: spectral optical model, computational fluid dynamics model and building energy simulation model. The method is demonstrated on a commercial building with double-skin facades and additionally, night-time ventilation.

Pérez-Grande et al. [44] studied the influence of glass properties on the performance of double-glazed facades. The total heat rate into the building has been calculated for 10 different facades formed by different glass combinations. The mass air flow rate in the channel, as well as the mean temperature increase of the air passing through the channel have also been predicted.

Chow and Hung [45,46] carried out experiments with physical scale models to investigate fire hazard of double-skinned facade (DSF). A facility developed in a remote area of Northeast China was selected for the full-scale burning tests on part of the DSF feature. Surface temperatures and heat flux received on the test panels were measured and analyzed. By examining the results for cavity depth of 0.5, 1.0 and 1.5 m, it is found that a deeper cavity might give better safety under the scenario studied. The outer glass panel would be broken rapidly for the cavity of 0.5 m deep. Double-skinned facade with a cavity of 1.0 m deep appeared to be very risky as glass panels above broke most among the different cavity depths.

Kuznik and Rusaouen [47] proposed a double-population thermal lattice Boltzmann method to solve the problem of the heated cavity with imposed temperatures. This family of problems can be considered as a test model for building physics application. A Taylor series expansion and least-square-based lattice Boltzmann method have been implemented in order to use a non-uniform mesh. To demonstrate the possibilities of the method described in the article, applications are described covering double-skin facades and solar collectors or local heaters.

Coussirat et al. [48] carried out several modeling tests on a well-documented experimental test case taken from the open literature in order to obtain a suitable model of the thermo-fluid-dynamics effects. Fluid and solid phase temperatures for a double-glazed facade configuration were obtained for three different radiation models and five different turbulence models, compared with experimental results available in the literature, and validated according to numerical verification and validation methodologies.

Eicker et al. [49] quantified the thermal performances of single and double facades under summer conditions using laboratory and full scale building experiments. Experimental results were used for model validation and parameter studies were done using dynamic building simulation tools. If the facade is used for providing fresh air to the room with an air exchange rate below two per hour, additional cooling loads of 2–5 kWh/m^2 room occur compared to ambient air ventilation (for blind absorption coefficient of 10 and 30%, respectively).

Høseggen et al. [50] described how a double-skin facade with controllable windows and hatches for natural ventilation can be implemented in the simulation program. The simulation results indicate that the energy demand for heating is about 20% higher for the single-skin facade with the basic window solution compared to the double-skin alternative.

Ji et al. [51] described computational fluid dynamics modeling of naturally ventilated double-skin facades (DSF) with Venetian blinds inside the facade cavity. The 2D modeling work investigates the coupled convective, conductive and radiative heat transfer through the DSF system. A series of angles of the Venetian blind (0°, 30°, 45°, 60° and 80°) have been modeled. The simulation results showed that the presence of Venetian blinds had little effect on the convective heat transfer coefficient at the glazing surfaces.

Marques da Silva and Glória Gomes [52] referred to a set of wind tunnel tests made over a building model with different multi-storey double skin facade layouts from open on all edges to full lateral closure and from narrow to wide gap depths, for an extended range of wind directions. The experimental data showed a layout dependent inner wall pressure distribution that may be considerably different from an unsheltered building.

Wong et al. [53] used computational fluid dynamics to analyze the possibilities of natural ventilation in an 18-storey high-rise office building in a hot and humid climate condition using double-skin facade. The results showed that the South-facing facade had the best outcome following by the East-facing facade during the morning period in the month of January. The North-facing and the West-facing facades did not provide an acceptable indoor thermal comfort for the purposes of office function in a high-rise building.

The optimum air gap size for the double-skin facade construction was found to be 300 mm and the best results were obtained during the morning period.

Xu and Yang [54] made a detailed analysis of the thermal process in glass double facade with venetian blind. The governing equations were solved by comprising computational fluid dynamics, optical and heat balance models for multi-layer transparent systems. It is shown that more complex natural ventilation exists in the two air gaps divided by venetian blinds, which cannot be reflected with the simplified model.

Dalal et al. [55] conducted a numerical study of steady free convection in a double glazed window with a between-panes pleated cloth blind. The study considers the effects of Rayleigh number, enclosure aspect ratio, and blind geometry on convective heat transfer. A simplified model of the coupled convective and radiative heat transfer is also presented. Sample results showed that the average Nusselt number data from the computational fluid dynamics study can be combined with a one-dimensional model to closely predict the glazing-to-glazing U-value.

Kim et al. [56] examined the contribution of a double skin envelope (DSE) to the heating energy savings brought about by natural ventilation in office buildings. Field measurements and computer simulations were performed in winter. Of all variables, the outdoor air temperature was the most significant factor influencing the air temperature in the cavity. Computer simulation indicated that the air in the cavity was heated to the required temperature without consuming additional energy when the ratio of the diffused irradiance to global irradiance was smaller than 0.69. This occurred for 17 days during January. On those days, the total amount of indoor air could be replaced a minimum of 0.81 times, and a maximum of 19.35 times per day. The cavity in the DSE worked as a thermal buffer zone and contributed to reducing heating energy consumption by 14.71% in January.

Laouadi [57] developed a general methodology to compute the thermal performance of complex fenestration systems. The methodology assumes each system layer as porous with calculated effective radiation and thermal properties. This methodology was validated using the available measurement and computational fluid dynamics simulation results for the U-factor of double-glazed windows with between-pane and internal blinds.

Tanaka et al. [58] investigated the three-dimensional thermal characteristics of double-skin facades that had the ventilation opening installed partially and were screened partially by the adjacent buildings by field measurements. To that end, field measurements were carried out on the double-skin exterior wall (9.4 m high and 27.0 m wide) installed in an atrium located in the west of an existing building during cooling period for typical summer conditions. Maximum air change rate of natural ventilation through the bottom opening up to the top opening was about 20–25 l/h and the reduction ratio of total solar heat gain compared with those of non-natural ventilation was about 25%.

3.1.2. Feasibility study

Gratia and De Herde [59–66] conducted several studies to analyze the impact of the double-skin facade (DSF) orientation and the impact of the wind orientation and the degree of wind protection during a sunny summer day in an office building. They also studied the impact of these parameters: solar radiation level, orientation and shading devices use, opaque wall/window proportion of the interior facade, wind speed, colour of shading devices and of interior facade, depth of the cavity of the DSF, glazing type in the interior facade and openings in the DSF on the mean air temperature evolution in the cavity. They concluded that the addition of a DSF always causes an increase in cooling loads and proposed the application of natural cooling strategies in order to reduce the energy cost of the building with DSF.

Rey [67] presented a synthesis of the research carried out with the support of the Swiss Academy of Engineering Sciences (SATW) and the Swiss National Energy Research Foundation (NEFF) in the framework of the European Master in Architecture and Sustainability to develop a multicriteria assessment methodology for office building retrofitting strategies applied to different case studies. The third case study was of the Cours de Rive office building in Geneva (1976–1978), which is representative of the period which lasts from the petroleum crisis to the end of the 1980s. For this building, the double-skin facade strategy presented the highest level of performances.

Zerefos [68] compared the heating and cooling loads between a double skin facade and a single skin facade in different and contrasting climates. The thermal and lighting properties of both types of facades are calculated, based on the hypothesis of a virtual south facing office room. The results showed that in climates with high sunshine duration, the difference in heating and cooling loads is less for a double skin facade in comparison to a single skin facade. This difference ranges from about 30% in the Mediterranean to about 40% in the Arabian peninsula in the case that the single skin building is not equipped with automatic shading devices, whereas in the case that both buildings have automatic shading devices the above percentages range from about 5.5% to 7.5%, respectively.

Baldinelli [69] presented the analysis of a glass double skin facade equipped with integrated movable shading devices, employing three different modeling levels: optics of materials, fluid dynamics of the double skin facade and building energy balance; the aim is to optimize both winter and summer energy performance. The model is developed for a facade oriented towards the south and taking into account the climatic data of central Italy. The facade performance was compared with traditional enclosures such as glazed and opaque walls in an office room in central Italy, showing an energy saving up to 60 kWh per year per facade square meter.

Chan et al. [70] reported the findings on the energy performance of a double skin facade applied to a typical office building under the climatic condition in Hong Kong. An experimental setup was established and the measured data was used to verify the theoretical model developed via the EnergyPlus simulation program. The results indicated that a double skin facade system with single clear glazing as the inner pane and double reflective glazing as the outer pane can provide an annual saving of around 26% in building cooling energy, as compared to a conventional single skin facade with single absorptive glazing. However, the long payback period of 81 years makes the double skin facade system economically infeasible.

Carlos et al. [71] characterized the thermal performance of a window system that consists in doubling an existing window, converting it into a ventilated double window. The air coming from the outside circulates upwards through the channel between windows and enters the building through a vent on the top of the window's case. A series of experimental measurements were conducted in a test cell exposed to real outdoor weather conditions located in a mountain region in the centre of Portugal, during heating season. An average of about 19 m^3/h of air flow rate was found with an air temperature increment within the air gap of about 6 °C, during night-time, for an indoor/outdoor temperature difference of about 16 °C. With solar radiation, the average of that increment was about 10 °C.

3.1.3. Application example

Kim et al. [72] presented the results of comfort survey and measurements on the indoor environment of an architecturally significant small glazed-envelope building. During the late summer of 2002, the comfort survey was conducted, polling responses from 57 office workers and measuring air/surface temperatures and daylight factors. Numerical simulations were performed to investigate

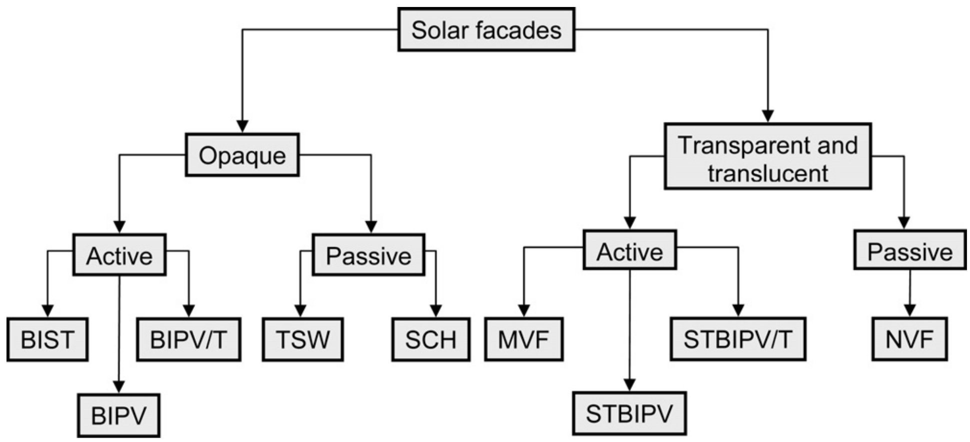


Fig. 7. Solar facades classification (BIST: building-integrated solar thermal system, BIPV: building integrated photovoltaic system, BIPV/T: building-integrated photovoltaic thermal system, TSW: thermal storage wall, SCH: solar chimney, MVF: mechanically ventilated facade, STBIPV: semi-transparent building-integrated photovoltaic system, STBIPV/T: semi-transparent building-integrated photovoltaic–thermal system and NVF: naturally ventilated facade).

13 design approaches for the improvement of the comfort level. From the numerical analysis using computer simulations, double-skin envelopes with the sufficient intermediate space and shading devices were suggested to improve the comfort level.

Xu and Ojima [73] proposed in this research a double skin facade for a two-story house in Kitakyushu, Japan. The temperature distributions, thermal performance in the double skin space and its impact on air-conditioning load in rooms have been obtained. Results showed that the double skin facade leads to about 10–15% energy savings for cooling in the peak of summer because of heat exhausted by natural ventilation and 20–30% energy savings for heating in winter because of the green house effect.

Altan et al. [74] reported the initial findings of an internal assessment of the thermal comfort and day lighting conditions in a building located in Sheffield, England. It has a high thermal mass which is used to promote the use of night cooling. The results have indicated that such designs are to be commended for their passive use of solar energy and can provide a high quality working environment.

Zhou and Chen [75] described the existing main research methods on the thermal performance of double-skin facade (DSF) and the shading devices. Problems and possibilities are concomitant. Applying ventilated DSF with a controlled shading device system would be a new efficient way for commercial buildings in the hot-summer and cold-winter zone to meet the task of sustainable building design in China (Fig. 7).

4. Conclusions

A detailed literature survey of studies carried out during the last 10 years in transparent and translucent solar facades has been performed. The studies reviewed were grouped into the following four systems: mechanically ventilated facade (MVF), semi-transparent building-integrated photovoltaic system (STBIPV), semi-transparent building-integrated photovoltaic–thermal system (STBIPV/T) and naturally ventilated facade (NVF).

Ventilated facades (MVF and NVF) are gaining remarkable recognition as an architectural element in office buildings. Beyond the aesthetic, these facades protect the building from adverse weather and noise and also reduce the heating (winter) and cooling (summer) loads of the building. Special attention is being devoted to the study of shading devices (e.g. venetian blinds, concrete thermal mass) located in the ventilation channel of the facade with the aim of reducing direct solar gain into the building.

Semi-transparent building-integrated photovoltaic systems (STBIPV and STBIPV/T) provide electricity, natural daylight and heat to the building. This technology is still at an early stage of development.

The present study allows the authors to state that, despite a few exceptions (Chan et al. [70], for instance), researchers neglect to consider the technico-economical feasibility of all the technologies surveyed herein. For most of them, the performance is either extrapolated, deducted or calculated from numerical predictions or measurements. In very few papers the energetic performance or efficiency is translated into a simple payback period. In the future, the authors, of course, should address more thoroughly, this critical issue.

This study concludes with the following figure which is an attempt to summarize all the technologies belonging to the family of solar facades.

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References

[1] Baker PH, McEvoy M. Test cell analysis of the use of a supply air window as a passive solar component. Solar Energy 2000;69:113–30.
[2] McEvoy ME, Southall RG, Baker PH. Test cell evaluation of supply air windows to characterise their optimum performance and its verification by the use of modelling techniques. Energy and Buildings 2003;35: 1009–20.
[3] Southall RG, McEvoy ME. Investigations into the functioning of a supply air window in relation to solar energy as determined by experiment and simulation. Solar Energy 2006;80:512–23.
[4] Zöllner A, Winter ERF, Viskanta R. Experimental studies of combined heat transfer in turbulent mixed convection fluid flows in double-skin-facades. International Journal of Heat and Mass Transfer 2002;45:4401–8.
[5] Safer N, Woloszyn M, Roux JJ. Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin facade equipped with a venetian blind. Solar Energy 2005;79:193–203.
[6] Balocco C, Colombari M. Thermal behaviour of interactive mechanically ventilated double glazed facade: non-dimensional analysis. Energy and Buildings 2006;38:1–7.
[7] Gosselin JR, Chen Q. A computational method for calculating heat transfer and airflow through a dual-airflow window. Energy and Buildings 2008;40: 452–8.
[8] Jiru TE, Haghighat F. Modeling ventilated double skin facade—a zonal approach. Energy and Buildings 2008;40:1567–76.

[9] Guardo A, Coussirat M, Egusquiza E, Alavedra P, Castilla RA. CFD approach to evaluate the influence of construction and operation parameters on the performance of Active Transparent Facades in Mediterranean climates. Energy and Buildings 2009;41:534–42.
[10] Haase M, Marques da Silva F, Amato A. Simulation of ventilated facades in hot and humid climates. Energy and Buildings 2009;41:361–73.
[11] Fuliotto R, Cambuli F, Mandas N, Bacchin N, Manara G, Chen Q. Experimental and numerical analysis of heat transfer and airflow on an interactive building facade. Energy and Buildings 2010;42:23–8.
[12] Gavan V, Woloszyn M, Kuznik F, Roux J-J. Experimental study of a mechanically ventilated double-skin facade with venetian sun-shading device: a full-scale investigation in controlled environment. Solar Energy 2010;84:183–95.
[13] Serra V, Zanghirella F, Perino M. Experimental evaluation of a climate facade: energy efficiency and thermal comfort performance. Energy and Buildings 2010;42:50–62.
[14] Corgnati SP, Perino M, Serra V. Experimental assessment of the performance of an active transparent facade during actual operating conditions. Solar Energy 2007;81:993–1013.
[15] Fallahi A, Haghighat F, Elsadi H. Energy performance assessment of double-skin facade with thermal mass. Energy and Buildings 2010;42:1499–509.
[16] Saelens D, Roels S, Hens H. Strategies to improve the energy performance of multiple-skin facades. Building and Environment 2008;43:638–50.
[17] Haase M, Amato A. A study of the effectiveness of different control strategies in double skin facades in warm and humid climates. Journal of Building Performance Simulation 2009;2:179–87.
[18] Fung TYY, Yang H. Study on thermal performance of semi-transparent building-integrated photovoltaic glazings. Energy and Buildings 2008;40:341–50.
[19] Song J-H, An Y-S, Kim S-G, Lee S-J, Yoon J-H, Choung Y-K. Power output analysis of transparent thin-film module in building integrated photovoltaic system (BIPV). Energy and Buildings 2008;40:2067–75.
[20] Han J, Lu L, Yang H. Thermal behavior of a novel type see-through glazing system with integrated PV cells. Building and Environment 2009;44:2129–36.
[21] Park KE, Kang GH, Kim HI, Yu GJ, Kim JT. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy 2010;35:2681–7.
[22] Phani G, Tulloch G, Vittorio D, Skryabin I. Titania solar cells: new photovoltaic technology. Renewable Energy 2001;22:303–9.
[23] Xu X, Dessel SV, Messac A. Study of the performance of thermoelectric modules for use in active building envelopes. Building and Environment 2007;42:1489–502.
[24] Xu X, Van Dessel S. Evaluation of a prototype active building envelope window-system. Energy and Buildings 2008;40:168–74.
[25] Xu X, Dessel SV. Evaluation of an active building envelope window-system. Building and Environment 2008;43:1785–91.
[26] Mercaldo LV, Addonizio ML, Noce MD, Veneri PD, Scognamiglio A, Privato C. Thin film silicon photovoltaics: architectural perspectives and technological issues. Applied Energy 2009;86:1836–44.
[27] Spanos I, Duckers L. Expected cost benefits of building-integrated PVs in UK, through a quantitative economic analysis of PVs in connection with buildings, focused on UK and Greece. Renewable Energy 2004;29:1289–303.
[28] Alnaser NW, Flanagan R, Alnaser WE. Potential of making—over to sustainable buildings in the Kingdom of Bahrain. Energy and Buildings 2008;40:1304–23.
[29] Bahaj AS, James PAB, Jentsch MF. Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. Energy and Buildings 2008;40:720–31.
[30] Chow T-T, Qiu Z, Li C. Potential application of see-through solar cells in ventilated glazing in Hong Kong. Solar Energy Materials and Solar Cells 2009;93:230–8.
[31] Li DHW, Lam TNT, Chan WWH, Mak AHL. Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy 2009;86:722–9.
[32] Davidsson H, Perers B, Karlsson B. Performance of a multifunctional PV/T hybrid solar window. Solar Energy 2010;84:365–72.
[33] Infield D, Mei L, Eicker U. Thermal performance estimation for ventilated PV facades. Solar Energy 2004;76:93–8.
[34] Faggembauu D, Costa M, Soria M, Oliva A. Numerical analysis of the thermal behaviour of ventilated glazed facades in Mediterranean climates. Part I. Development and validation of a numerical model. Solar Energy 2003;75:217–28.
[35] Faggembauu D, Costa M, Soria M, Oliva A. Numerical analysis of the thermal behaviour of glazed ventilated facades in Mediterranean climates. Part II. Applications and analysis of results. Solar Energy 2003;75:229–39.
[36] Balocco C. A non-dimensional analysis of a ventilated double facade energy performance. Energy and Buildings 2004;36:35–40.
[37] Park C-S, Augenbroe G, Messadi T, Thitisawat M, Sadegh N. Calibration of a lumped simulation model for double-skin facade systems. Energy and Buildings 2004;36:1117–30.
[38] Park CSC-S, Augenbroe G, Sadegh N, Thitisawat M, Messadi T. Real-time optimization of a double-skin facade based on lumped modeling and occupant preference. Building and Environment 2004;39:939–48.
[39] Saelens D, Roels S, Hens H. The inlet temperature as a boundary condition for multiple-skin facade modeling. Energy and Buildings 2004;36:825–35.
[40] Ismail KAR, Henríquez JR. Two-dimensional model for the double glass naturally ventilated window. International Journal of Heat and Mass Transfer 2004;48:461–75.
[41] Xamán J, Álvarez G, Lira L, Estrada C. Numerical study of heat transfer by laminar and turbulent natural convection in tall cavities of facade elements. Energy and Buildings 2005;37:787–94.
[42] Hien WN, Liping W, Chandra AN, Pandey AR, Xiaolin W. Effects of double glazed facade on energy consumption, thermal comfort and condensation for a typical office building in Singapore. Energy and Buildings 2005;37:563–72.
[43] Manz H, Frank T. Thermal simulation of buildings with double-skin facades. Energy and Buildings 2005;37:1114–21.
[44] Pérez-Grande I, Meseguer J, Alonso G. Influence of glass properties on the performance of double-glazed facades. Applied Thermal Engineering 2005;25:3163–75.
[45] Chow WK, Hung WY. Effect of cavity depth on smoke spreading of double-skin facade. Building and Environment 2006;41:970–9.
[46] Chow WK, Hung WY, Gao Y, Zou G, Dong H. Experimental study on smoke movement leading to glass damages in double-skinned facade. Construction and Building Materials 2007;21:556–66.
[47] Kuznik F, Rusaouen G. Numerical prediction of natural convection occurring in building components: a double-population lattice Boltzmann method numerical heat transfer. Part A. Applications. An International Journal of Computation and Methodology 2007;52:315–35.
[48] Coussirat M, Guardo A, Jou E, Egusquiza E, Cuerva E, Alavedra P. Performance and influence of numerical sub-models on the CFD simulation of free and forced convection in double-glazed ventilated facades. Energy and Buildings 2008;40:1781–9.
[49] Eicker U, Fux V, Bauer U, Mei L, Infield D. Facades and summer performance of buildings. Energy and Buildings 2008;40:600–11.
[50] Høseggen R, Wachenfeldt BJ, Hanssen SO. Building simulation as an assisting tool in decision making: case study: with or without a double-skin facade. Energy and Buildings 2008;40:821–7.
[51] Ji Y, Cook MJ, Hanby V, Infield DG, Loveday DL, Mei L. CFD modelling of naturally ventilated double-skin facades with Venetian blinds. Journal of Building Performance Simulation 2008;1:185–96.
[52] Marques da Silva F, Glória Gomes M. Gap inner pressures in multi-storey double skin facades. Energy and Buildings 2008;40:1553–9.
[53] Wong PC, Prasad D, Behnia M. A new type of double-skin facade configuration for the hot and humid climate. Energy and Buildings 2008;40:1941–5.
[54] Xu X-L, Yang Z. Natural ventilation in the double skin facade with venetian blind. Energy and Buildings 2008;40:1498–504.
[55] Dalal R, Naylor D, Roeleveld D. A CFD study of convection in a double glazed window with an enclosed pleated blind. Energy and Buildings 2009;41:1256–62.
[56] Kim Y-M, Kim S-Y, Shin S-W, Sohn J-Y. Contribution of natural ventilation in a double skin envelope to heating load reduction in winter. Building and Environment 2009;44:2236–44.
[57] Laouadi A. Thermal performance modelling of complex fenestration systems. Journal of Building Performance Simulation 2009;2:189–207.
[58] Tanaka H, Okumiya M, Tanaka H, Young Yoon G, Watanabe K. Thermal characteristics of a double-glazed external wall system with roll screen in cooling season. Building and Environment 2009;44:1509–16.
[59] Gratia E, De Herde A. Is day natural ventilation still possible in office buildings with a double-skin facade. Building and Environment 2004;39:399–409.
[60] Gratia E, De Herde A. Natural cooling strategies efficiency in an office building with a double-skin facade. Energy and Buildings 2004;36:1139–52.
[61] Gratia E, De Herde A. Natural ventilation in a double-skin facade. Energy and Buildings 2004;36:137–46.
[62] Gratia E, De Herde A. Optimal operation of a south double-skin facade. Energy and Buildings 2004;36:41–60.
[63] Gratia E, De Herde A. Are energy consumptions decreased with the addition of a double-skin. Energy and Buildings 2007;39:605–19.
[64] Gratia E, De Herde A. Greenhouse effect in double-skin facade. Energy and Buildings 2007;39:199–211.
[65] Gratia E, De Herde A. Guidelines for improving natural daytime ventilation in an office building with a double-skin facade. Solar Energy 2007;81:435–48.
[66] Gratia E, De Herde A. The most efficient position of shading devices in a double-skin facade. Energy and Buildings 2007;39:364–73.
[67] Rey E. Office building retrofitting strategies: multicriteria approach of an architectural and technical issue. Energy and Buildings 2004;36:367–72.
[68] Zerefos SC. On the performance of double skin facades in different environmental conditions. International Journal of Sustainable Energy 2007;26:221–9.
[69] Baldinelli G. Double skin facades for warm climate regions: analysis of a solution with an integrated movable shading system. Building and Environment 2009;44:1107–18.
[70] Chan ALS, Chow TT, Fong KF, Lin Z. Investigation on energy performance of double skin facade in Hong Kong. Energy and Buildings 2009;41:1135–42.
[71] Carlos JS, Corvacho H, Silva PD, Castro-Gomes JP. Real climate experimental study of two double window systems with preheating of ventilation air. Energy and Buildings 2010;42:928–34.
[72] Kim K, Kim BS, Park S. Analysis of design approaches to improve the comfort level of a small glazed-envelope building during summer. Solar Energy 2007;81:39–51.
[73] Xu L, Ojima T. Field experiments on natural energy utilization in a residential house with a double skin facade system. Building and Environment 2007;42:2014–23.
[74] Altan H, Ward I, Mohelnikova J, Vajkay F. An internal assessment of the thermal comfort and daylighting conditions of a naturally ventilated building with an active glazed facade in a temperate climate. Energy and Buildings 2009;41:36–50.
[75] Zhou J, Chen Y. A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. Renewable and Sustainable Energy Reviews 2010;14:1321–8.